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WILDFIRES IMPACT ON HYDROLOGICAL RESPONSE – THE CASE OF LYKORREMA EXPERIMENTAL WATERSHED

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ABSTRACT

One of the issues that have recently attracted increased attention from the hydrologic community is the impact of forest fires on the hydrological response of the once vegetated areas. This study presents the investigation of wildfires impact on the hydrological response of the small scale experimental watershed of Lykorrema stream, which is located in the east side of Penteli Mountain, Attica, Greece. In the recent years, the watershed was affected by two wildfires in August 1995 and in August 2009. The effect of the August 1995 wildfire on the peak runoff was investigated in a previous study, in which an increment of 10 times in peak runoff was observed. This paper presents the results of an analysis concerning the impact of the second wildfire on the watershed's hydrological response based on the available detailed spatial physical and hydro-meteorological data. The results obtained highlight the considerable impact of forest fire on the watersheds hydrological response. An increment in the direct runoff depths and the peak flow rates as much as 230% and 850% respectively was observed during the first two years of the post-fire period.

KEYWORDS: forest fires, peak runoff, direct runoff, post-fire recovery.

INTRODUCTION

Forest fires are an integral part of Mediterranean ecosystems. However, climate change in combination with human intervention and the lack of forest management significantly increase forest fire hazard. As a result, in recent years, especially in northern Mediterranean countries, an important surge in catastrophic forest fire incidents has been observed (European Commission, 2002). Thus, wildfires have emerged as increasingly dominant drivers of ecosystem functioning (Pausas *et al*., 1999). This has led to a new awareness about the effects of forest fires, not only in terms of vegetation loss, but also of probable loss of life and property, as well as of changes in the hydrological response and erosion/sedimentation process of the once vegetated areas (Rulli and Rosso, 2007). Several studies have pointed out the impact of forest fires on the hydrological cycle, including reduced infiltration rates, reduced evapotranspiration rates and increased overland flow. Such impact is mainly attributed to the destruction of the vegetation cover and the consequent direct influence on interception, evapotranspiration and overland flow velocity (Robichaud, 2000; 2005; Prosser and William, 1998; Pierson *et al*., 2001; 2002; 2008). However, forest fires can also affect hydrological processes indirectly, altering the hydraulic properties of the soil (Giovannini and Lucchesi, 1983; Gionannini *et al*., 1988; Lavabre *et al*., 1993). Fires destroy the top soil organic matter destabilizing the soil structure, they convert the organic ground cover to soluble ash, and give rise to phenomena such as water repellency (Imeson *et al*., 1992; Neary *et al*., 1999). Water repellency is an abnormality in soils, which results from the coating of soil particles with organic substances reducing the affinity shown by the soil for water (DeBano, 2000).

Fire impact on hydrological processes is normally apparent for one or two years after the wildfires (Marques and Mora, 1992; Cerdà, 1998). However, in dry areas, much higher runoff and erosion rates are being noticed even five to ten years after the fire (Inbar *et al*., 1998; Robichaud, 2000; Mayor *et al*., 2007). The period necessary for the hydrological process recovery to the pre-fire conditions greatly depends on the rate of vegetation recovery. Previous studies have shown that the period necessary for runoff and soil erosion to return to background levels depends on the type of species existing prior to fire, because each species has its own specific recovery rate. It has also been found that the amount of litter and vegetation cover is a key factor in reducing post-fire runoff and erosion, and in accelerating the recovery time of burned soils (Inbar *et al*., 1998; Vega *et al*., 2005; Cerda, 1998; Marcos *et al*., 2000; De Luis *et al*., 2003); however, in dry areas, water shortage can seriously limit plant growth rate (Mayor *et al*., 2007). The plant recovery and the recovery of post-fire hydrological responses may be constrained by factors, which are common in Mediterranean countries, such as harsh meteorological and hydrological conditions (Inbar *et al*., 1998; Mayor *et al*., 2007), plant communities with low regeneration potential that have colonized abandoned fields (Pausas *et al*., 1999), highly erodible soils, and steep slopes (Yassoglou, 1995). Other factors influencing the post-fire restoration process are burn severity, post-fire management, silvicultural treatments, grazing etc. (Li *et al*., 2006; Spanos *et al*., 2000; 2010; Martinez–Sanchez *et al*., 1999; De las Heras *et al*., 2004). South-facing slopes have also been reported as particularly sensitive to wildfire impact (Marques and Mora, 1992; Andreu *et al*., 2001) highlighting the vast spatial and temporal variability.

Despite the relative abundance of plot-scale field experiments, a comprehensive knowledge of fire effects at the catchment scale is still lacking (Rulli and Rosso, 2007). In contrast, relatively large spatial and temporal scales are needed to assess post-fire ecosystem dynamics given both the spatial heterogeneity of Mediterranean landscapes and the temporal variation in control factors, particularly in rainfall patterns (Moody and Martin, 2001; Mayor *et al*., 2007). Particularly in Greece, mainly due to the lack of systematic hydro-meteorological data, the spatio-temporal impact of forest fires on the watersheds hydrological response has been studied inadequately or to a very limited extent.

This study presents an investigation of wildfires impact on the hydrological response of the small scale experimental watershed of Lykorrema stream, which is located in the east side of Penteli Mountain, Attica, Greece. The Lykorrema experimental watershed is organized, operated, and systematically studied by the Water Resources Management Division of the Agricultural University of Athens. Detailed geographical and hydro-meteorological databases have been available for this watershed since 2004 (Soulis, 2009; Soulis *et al*., 2009a; Soulis and Valiantzas, 2011). In the recent years, the watershed was affected by two wildfires in August 1995 and in August 2009. Prior to the first wildfire, the watershed was mainly covered by a dense pine forest, while a small part of the watershed, around the top of the hills, was covered with shrubs or bare rock. The pine forest was almost totally destroyed by the 1995 wildfire. Prior to the second fire, the watershed had a mixed vegetation cover consisting of pasture, scrublands, and pine forest at the first stage of development.

In a previous study, Soulis *et al*. (2009b) investigated the impact of the August 1995 wildfire on peak runoff values by indirect measurements of the maximum flow rates during the post-fire period and by the study of the physical - hydraulic properties of the watershed's soils before and after the impact of fire. They observed an increment in peak runoff values as much as 10 times for the period soon after the first wildfire, compared to the period soon before the second wildfire. The authors concluded that both the destruction of the vegetation cover and the reduction of the soil infiltration capacity influence the increment of peak runoff values and that these changes have led to a significant increase of flood risk.

Within this frame, this paper presents the results of a research concerning the impact of the second wildfire on the watershed's hydrological response based on the available detailed spatial data and hydro-meteorological records. Furthermore, the observations concerning the post fire hydrological process recovery during the first two years after the latest forest fire incident are presented.

MATERIALS AND METHODS

Study Area

The study area is the small scale experimental watershed of Lykorrema stream (7.84km^2), located in the east side of Penteli Mountain, Attica, Greece (Coordinates: UL 23°53’33”E-38°04’13”N; LR 23°56’00”E-38°02’28”N) (Figure 1). The region is characterized by a Mediterranean semi-arid climate with mild, wet winters and hot, dry summers. Precipitation occurs mostly in the autumn–spring period. The average annual precipitation for the six years studied (2004-2005 to 2009-2010) is 690 mm. The reference evapotranspiration rate varies from about 1mm/day during winter to 7 mm/day during summer. The Lykorrema watershed presents a relatively sharp relief, with elevations ranging between 280 m and 950 m. Its average elevation is 560 m and its average slope is as high as 36%. Geologically the watershed is characterized by schists formations covering 96% of the area, while the rest is covered by marbles. Schist formations in the area are not impervious. They are tectonically intensely fractured and their upper layer is eroded (Baltas *et al*., 2007). A soil survey in the area showed that the watershed is dominated by coarse soils with high hydraulic conductivities and a smaller part is covered with medium textured soils presenting relatively high hydraulic conductivities.

A detailed land cover classification based on remote sensing techniques carried out before the 2009 wildfire, showed that the watershed had a mixed vegetation cover consisting of pasture, shrublands, a pine forest at the first stage of development and a few scattered tufts of trees. There was also a dense network of forest roads, while a small part of the watershed was covered by bare rock (Figure 1a). The forest fire in August 2009 destroyed most of this vegetation cover as shown in Figure 1b. Using satellite imagery acquired soon after the wildfire, it was estimated that about 87% of the watershed’s vegetation cover was burnt.

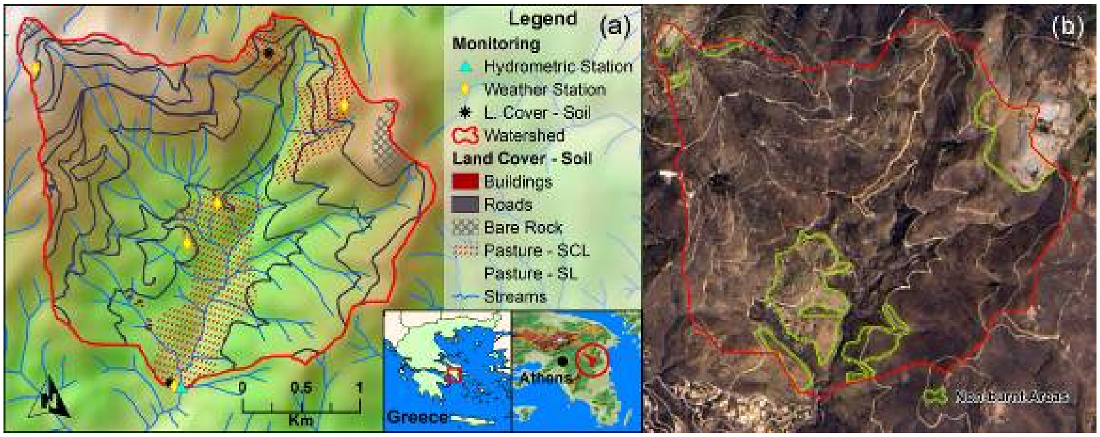

Figure 1. (a) Map of Lykorrema stream experimental watershed. (b) Satellite image of the watershed after the August 2009 wildfire

The aquifers system developed within the intensely fractured bedrock significantly contributes to the base flow of the watershed, which is continuous throughout the year. Generally, there is not an immediate response of base flow rate to the storm events. During wet years the base flow rate increases continuously till late spring whereas in dry years base flow rate decreases slowly throughout the year.

Monitoring and Sampling

The study area is equipped with a dense hydro-meteorological network, which is fully operational since September 2004. The network consists of five rain-gauges, one hydrometric station at the outlet of the watershed, one meteorological station and four temperature-relative humidity recorders (Figure 1a). The data that were used in this study are recorded with a time step of 10 min. The Lykorrema experimental watershed is operated by the Agricultural University of Athens.

Soon after the 2009 forest fire incident, undisturbed top-soil samples were collected at two sites, where soil samples were already collected before the fire (Figure 1a). Soil samples were collected again after the first autumn rainfalls, and one year after the fire. In addition, at the same sites, the vegetation cover recovery processes was frequently observed.

Data Analysis

For the current analysis, 59 storm events producing significant direct runoff that took place from September 2004 to March 2011 were used. A storm event was considered significant when the value of peak flow rate in the hydrograph was greater than 0.15 $m^3 s^{-1}$. The beginning and the end of an event were defined by rainless intervals of 3 h duration considering rainfall intensities greater or equal to 0.4 mm h^{-1}. The duration, the total rainfall depth, the peak hourly rainfall intensity, the direct runoff depth, and the peak flow rate were determined for each event. The Base Flow Index (BFI - the long-term proportion of base flow on total stream flow) values for the periods before and after the fire were determined as well. The watershed areal precipitation was estimated using the Thiessen polygons method, while base-flow was separated using the constant slope graphical method (Dingman, 2002). In order to investigate the impact of the forest fire on the soil properties, the Saturated Hydraulic Conductivity (*Ks*) of the collected undisturbed top-soil samples was estimated in the laboratory.

RESULTS AND DISCUSSION

Rainfall

Precipitation occurs mostly in the autumn–spring period. The average annual rainfall depth for the last six hydrological years is 690 mm, and ranges between 537 and 757 mm. The annual snowfall height in the area is normally low (10 to 20 cm). The rainfall depth during the first year after the fire (2009-2010) was relatively high (750 mm). During this 1 year period, 22 significant storm events were recorded. During the second year after the fire, the rainfall depth was also high (620 mm, since 27/3/2011), but only 7 significant storm events were recorded. The period before the fire (2004 – 2009), the average annual rainfall depth was 675 mm and a total of 30 significant storm events were recorded. More details on the characteristics of these events are presented in Figures 2 and 3.

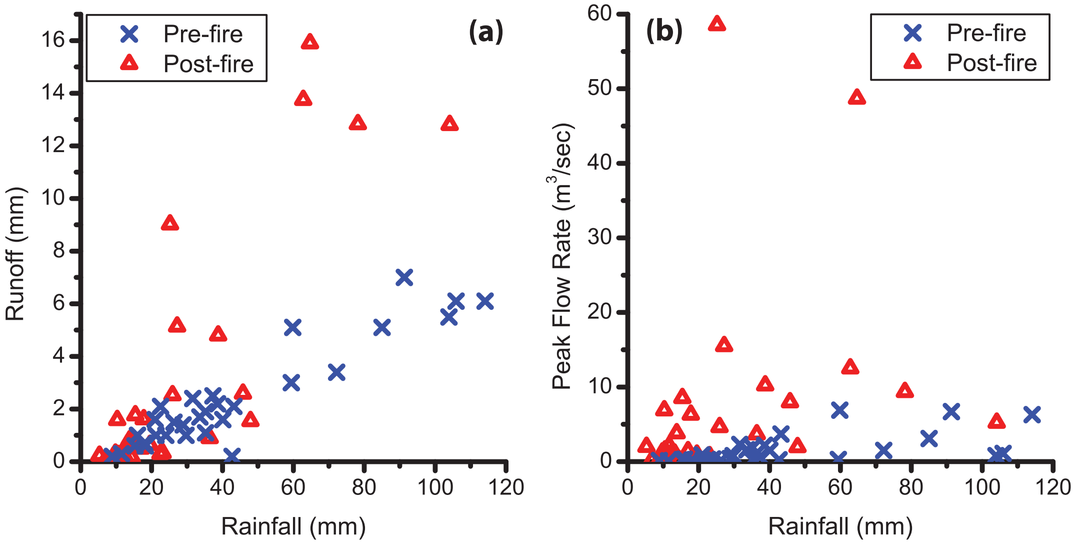

Figure 2. Rainfall depths vs: (a) direct runoff depth, and (b) peak flow rate, before and after the 2009 forest fire

Runoff Response

In Figure 2 the direct runoff depth and the peak flow rate are plotted against the rainfall depth for the periods before and after the August 2009 forest fire incident. It can be clearly seen that both the direct runoff depths and the peak flow rates observed the period after the forest fire are considerably higher compared to the period before the fire. The maximum direct runoff depth observed after the fire (15.9 mm) was about 230% higher than the one observed before the fire (7 mm). Accordingly, the maximum flow rate observed after the fire (58.55 m^3 sec^{-1}) was about 850% higher than the one observed before the fire (6.9 m^3 sec^{-1}). It must be noted that these results are in agreement with the results presented for the August 1995 forest fire incident by Soulis *et al*. (2009b). In that study, the maximum flow rate for the period soon after the fire was estimated using indirect measurements equal to 65 m^3 sec^{-1}.

It must be also noted that the total direct runoff depth for the studied period before the 2009 fire (5 years) was measured equal to 70 mm, while the total direct runoff depth for the period after the fire (1.5 years) was measured equal to 91.7 mm. Accordingly, the BFI for the pre-fire period was estimated equal to 0.79. The first year after the fire the estimated BFI was decreased to 0.56, while for the entire post-fire period (since 27/3/2011) the BFI was estimated equal to 0.54.

In Figure 3a the peak flow rate is plotted against the direct runoff depth in order to examine if the increased peak flow rates observed the period after the forest fire can be attributed to the increment of direct runoff depths alone. It can be observed that for the same direct runoff depths considerably higher peak flow rates are observed during the post-fire period. This can be attributed to the considerable decrease of the concentration time due to the destruction of the vegetation cover. In Figure 3b the peak flow rate is plotted against the maximum hourly rainfall intensity. It can be seen that following the forest fire, increased rainfall intensities are related to increased peak runoff values, which is not the case for the period before the forest-fire. This behaviour indicates that the forest fire may have an effect on the runoff generation processes (e.g. the forest fire could influence the peak runoff contributing area of the watershed) but more evidence is needed in order to justify this hypothesis.

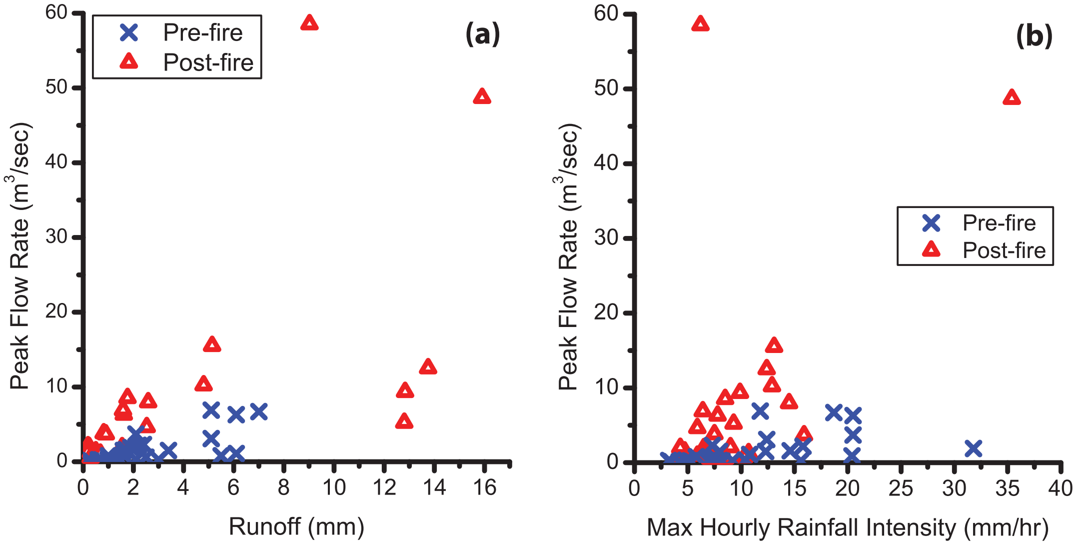

Figure 3. Peak flow rate vs. direct runoff depth (a) and peak flow rate vs. maximum hourly rainfall depth (b), before and after the 2009 forest fire

Soil Properties

The hydraulic conductivity, *Ks*, values measured for the soil samples collected soon after the forest fire were close to the corresponding *Ks* values measured for the samples collected before the fire (the $\overline{Ks}$ values at the two sampling sites are 9 cm h^{-1} and 15 cm h^{-1} respectively, while the sample standard deviation, *s*, is 4 cm h^{-1} and 9 cm h^{-1} respectively). In contrast, the *Ks* values measured for the soil samples collected after the first autumn rainfalls (23/9/2009) were significantly lower than the *Ks* values measured before and soon after the fire ($\overline{Ks} \approx$ 3.5 cm h^{-1} and 2.5 cm h^{-1}; $s \approx$ 3.7 cm h^{-1} and 0.7 cm h^{-1} at the two sites, respectively). The soil samples collected one year after the fire, were characterised by similar *Ks* values to the samples collected before the fire. Accordingly, it can be concluded that the forest fire had an influence on the soils *Ks*, but due to the very large variability on the measured *Ks* values it is difficult to provide safe conclusions. It is also remarkable that the fire influence on *Ks* appeared only after the effect of the first rainfall event. This observation is in accordance with the rainfall-runoff data recorded after the fire. Specifically, the first significant rainfall event after the fire (11/9/2009; rainfall depth, P = 36 mm) produced negligible runoff, while the following two very small rainfall events (12/9/2009; P = 17 mm and 14.4 mm) resulted in significant runoff and peak flow rates (see Figure 2). Following these events, a relatively small rainfall event (16/10/2009; P = 25.2 mm) produced a very high runoff depth (9 mm) and an extraordinary peak flow rate (58.55 m^3 sec^{-1}). It is also noted that 22 out of the total 29 storm events recorded after the fire occurred during the first post-fire period, which is in accordance with the Ks values measured one year after the fire.

The significantly decreased Ks values and the extraordinary peak runoff value observed after the first autumn rainfalls could be attributed to the formation of a crust on the soil surface under the effect of the forest fires and the rainfall. The effects of the forest fire on the soil surface are illustrated in Figure 4. In this figure the crust formed after the first autumn post-fire rainfalls can be clearly observed.

Figure 4. Effect of the forest fire on the soil surface: (a) before the first autumn rainfalls, (b, c) after the first autumn rainfalls

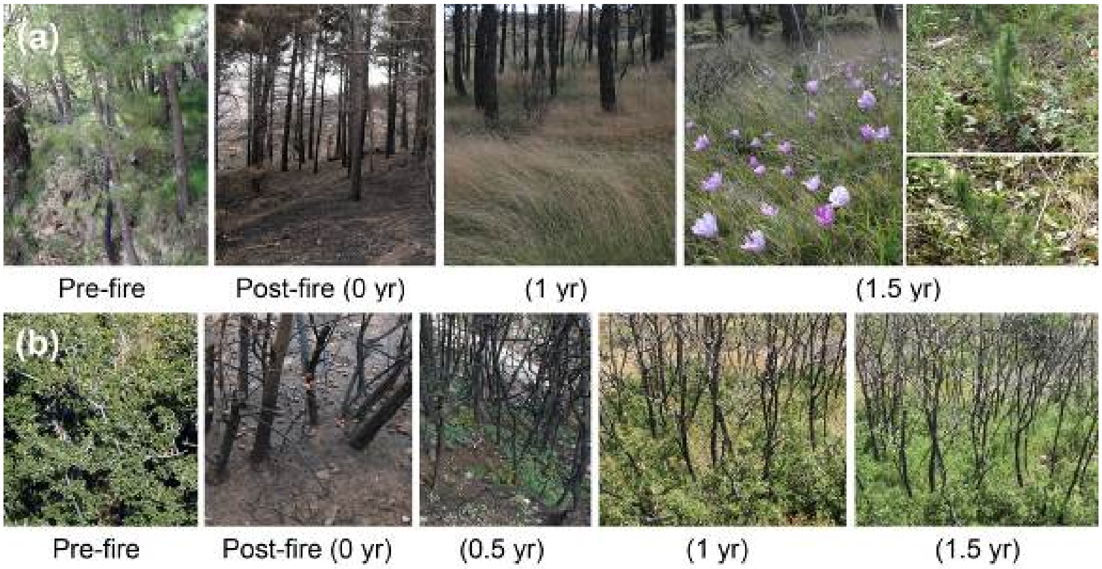

Figure 5. Illustration of the vegetation recovery process in the two sampling sites: (a) site covered by pine forest and (b)site covered by oak shrubs

Post-fire Vegetation Recovery

Post-fire vegetation recovery was very fast during the first year after the fire. During the first autumn after the fire, the bigger part of the watershed was already covered with grasses, and most of the bushes were rapidly regenerated. During the second autumn after the fire the shrublands continued to recover, assisted by the relatively wet weather during the first two years. However, the pine forest started to recover only in very small parts of the watershed. The rapid recovery of the grasslands and the shrublands may justify the quick recovery of the soil properties. The vegetation recovery process, in the two sampling sites that were covered by oak shrubs and by pine forest, is illustrated in Figure 5.

CONCLUSIONS

In this study the impact of a wildfire on the hydrological response of a small experimental watershed is investigated based on detailed spatial, physical and hydro-meteorological data. According to the obtained results direct runoff depths and peak flow rates increased considerably during the first year after the forest fire. Specifically, runoff depths increased as much as 2.3 times while peak flow rates were 8.5 times higher compared to the period before the fire. Thus, it can be concluded that the 2009 forest fire influenced the hydrological response of the Lykorrema experimental watershed. The data analysis indicated that the main ways in which wildfires influence flood risk are the destruction of the vegetation cover and the reduction of the soil infiltration capacity. Furthermore, the extraordinary high peak flow rates observed after the fire can be attributed to both the increased direct runoff produced and the decreased concentration times . There are also indications that the post fire hydrological process recovery is relatively fast. The observed changes in the hydrological response may significantly increase flood risk. Finally, the data collected and results obtained up to now can be proven very important; they allow the evaluation of the wildfires impact on watersheds' hydrological response under the local conditions.

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